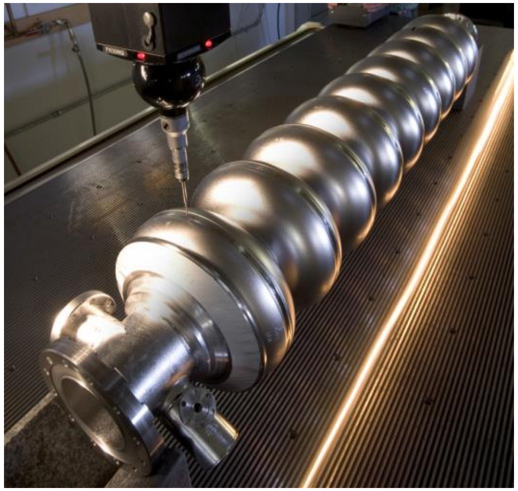
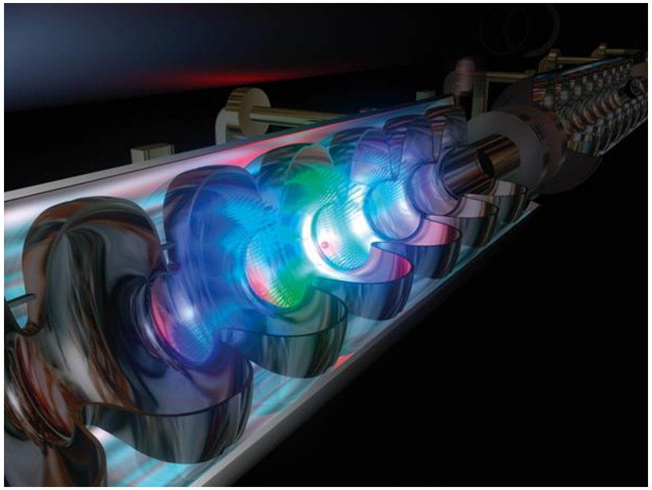
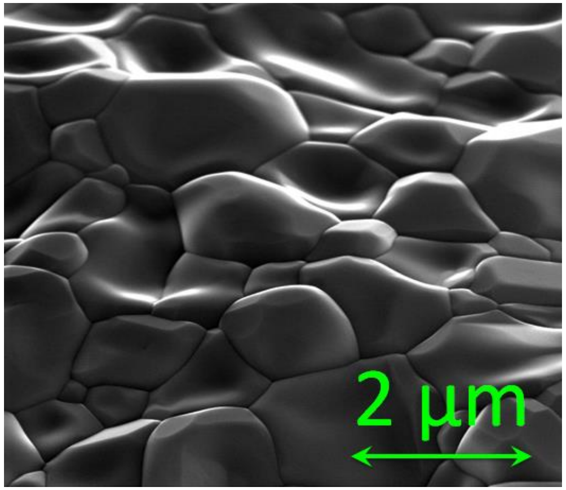
Magnetic Field Limits of Superconducting RF Cavities





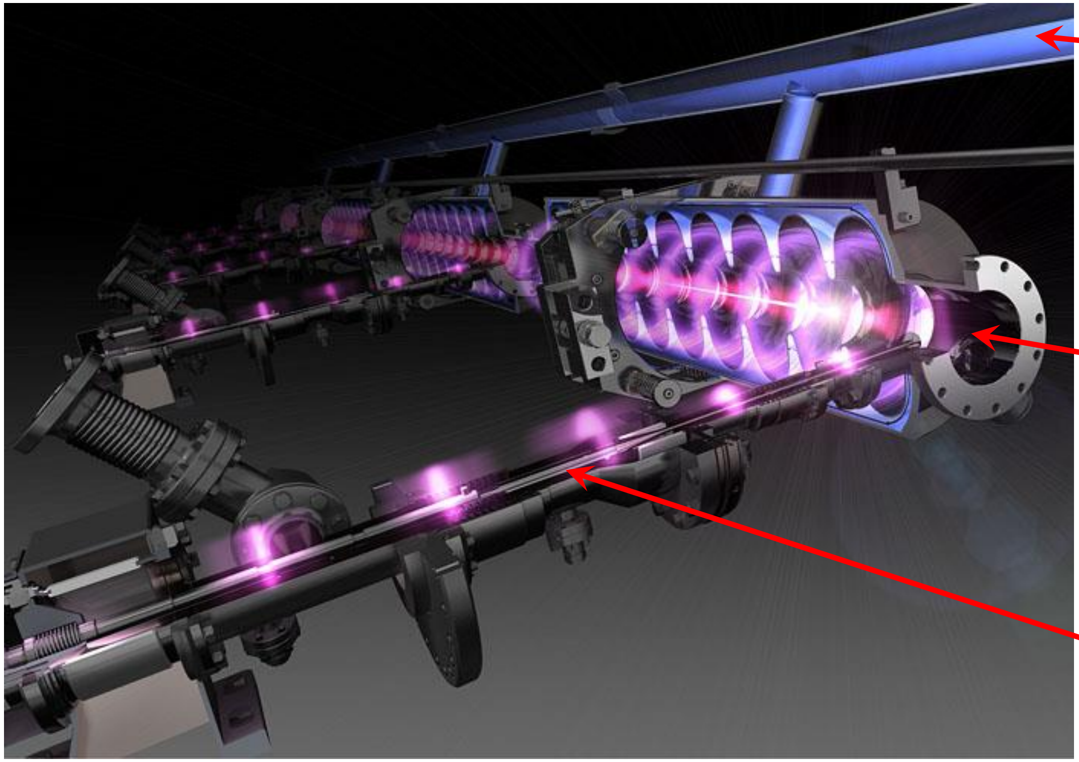


Sam Posen
Associate Scientist, FNAL Technical Division

Workshop on Microwave Cavity Design for Axion Detection
August 26, 2015

Some images from linearcollider.org

Superconducting RF Cavities



Liquid helium cooling

Particle beam

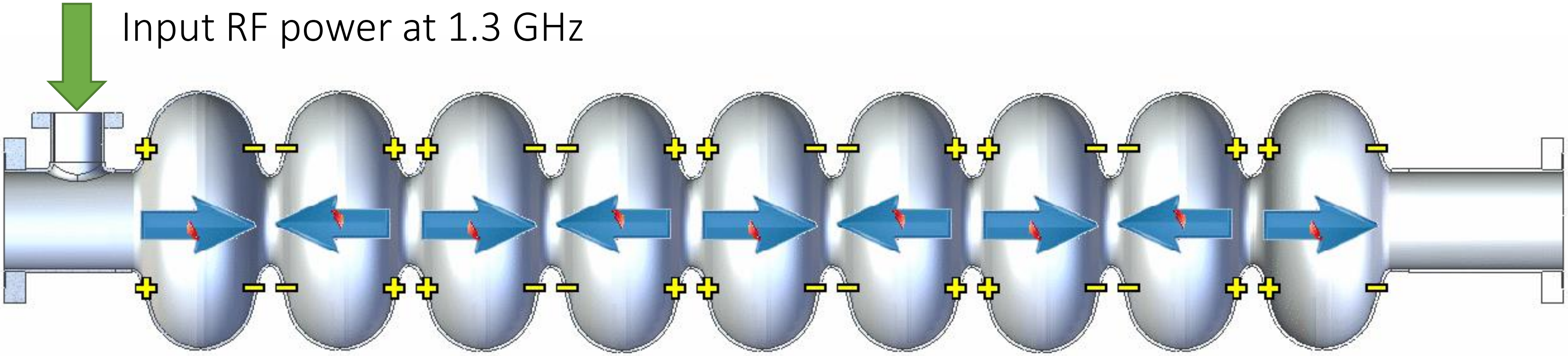
RF drive

- Muscle of many large particle accelerators
- RF input power → accelerating electric field

Image from linearcollider.org

SRF Accelerator Cavity

- SRF cavity: high quality EM resonator
- Particle beam gains energy as it passes through

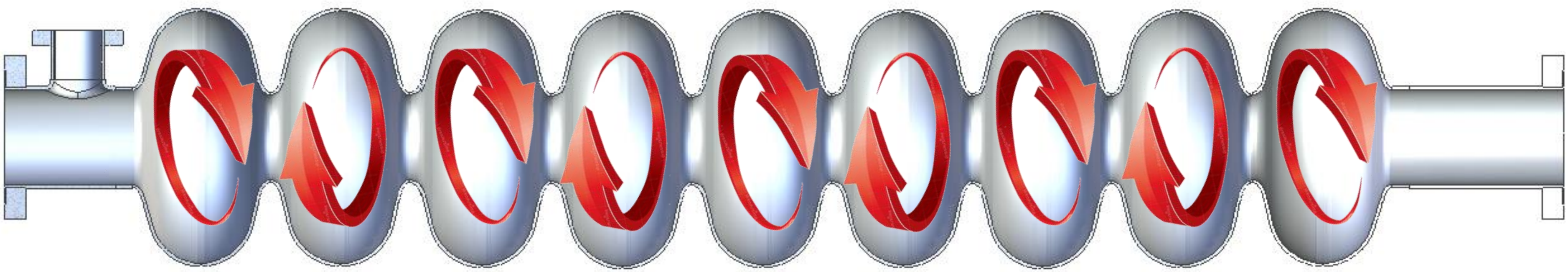


Slowed down by factor of approximately 4x10^9

- Electric field provides acceleration
- Magnetic field can't be avoided

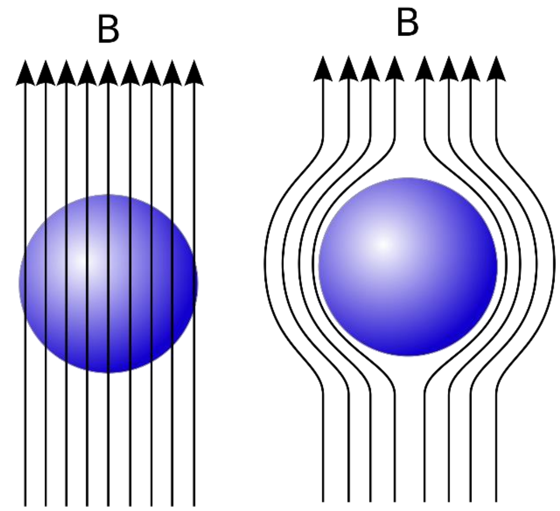
Superconductors and Magnetic Fields

- How high in field can we take SRF cavities?
- State of the art niobium cavities are limited by peak surface magnetic field

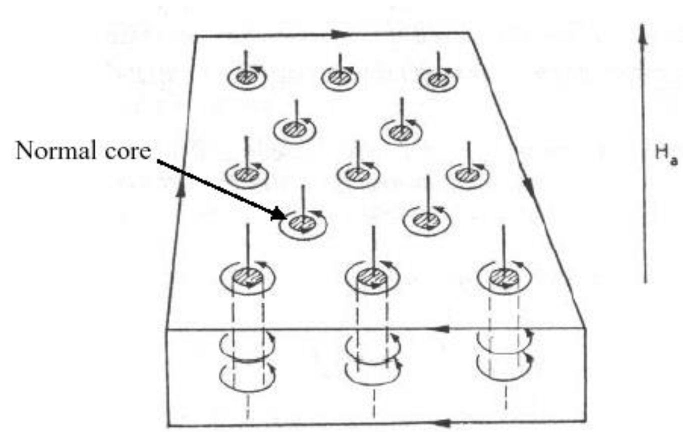


Superconductors and Magnetic Fields

- For relatively small applied magnetic fields, superconductors expel flux: Meissner state



- At higher fields, Type II superconductors allow flux to enter in packets: Vortex state

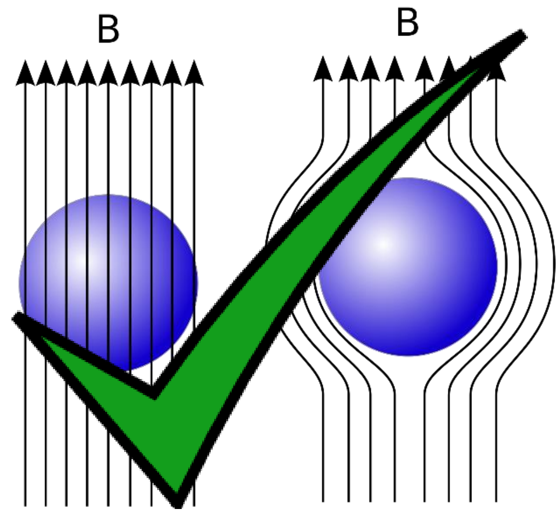


Images from Wikipedia and Rose-Innes and Roderick, Introduction to Superconductivity

Fermilab

Superconductors and Magnetic Fields

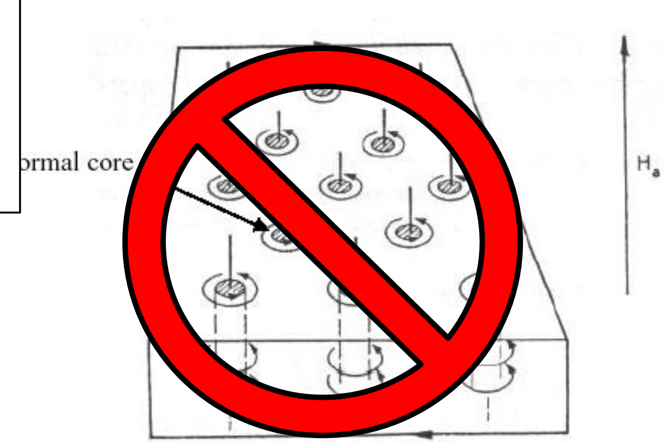
- For relatively small applied magnetic fields, superconductors expel flux: Meissner state



Avoid flux penetration.

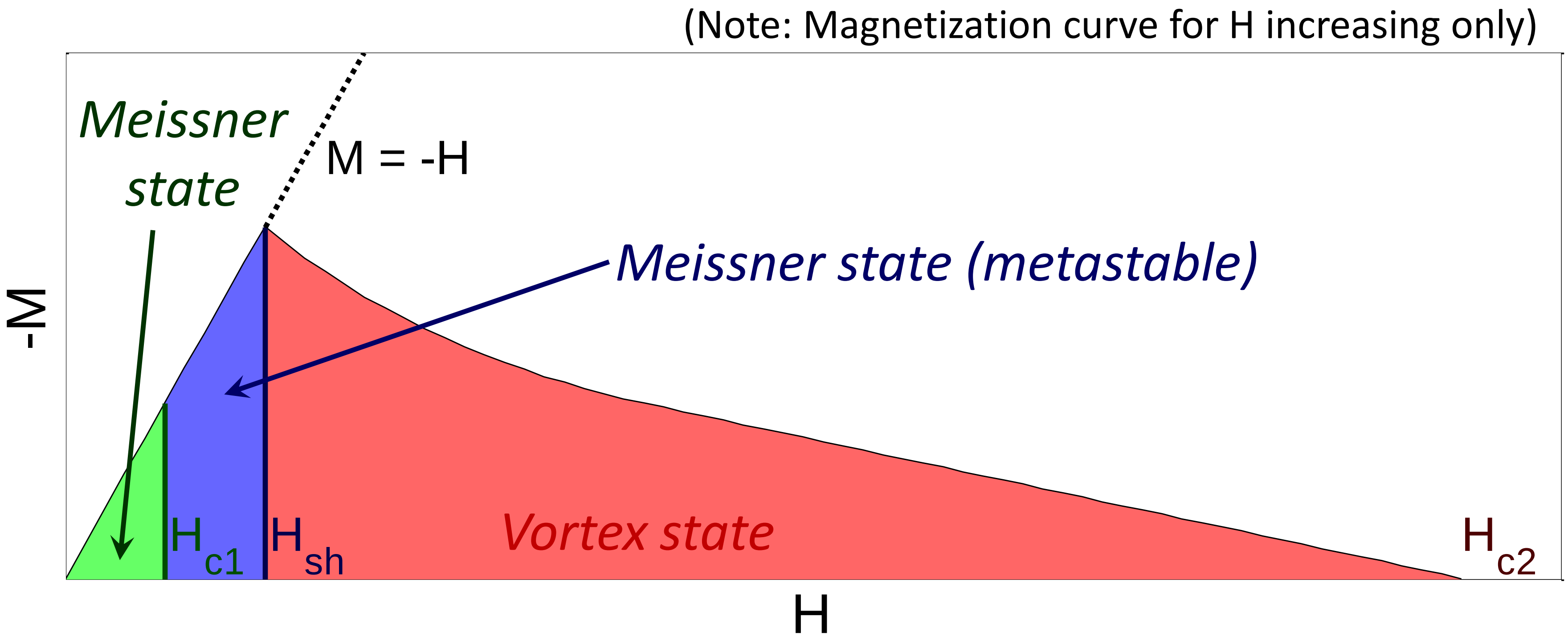
At RF frequencies → *excessive heating*

state



Images from Wikipedia and Rose-Innes and Roderick, Introduction to Superconductivity

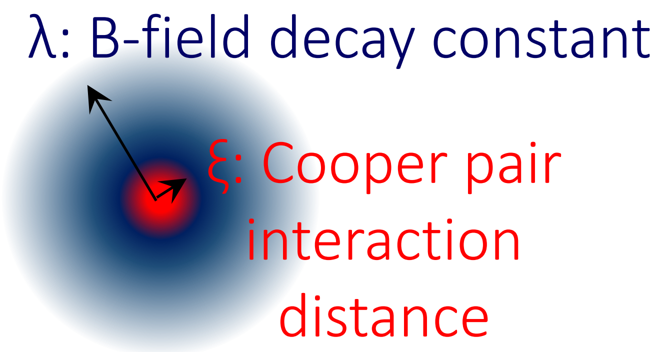
Superheating Field



- Flux free Meissner state is stable up to H_{c1}
- Favorable for flux to be deep in bulk above H_{c1}
- BUT surface energy barrier allows metastable state!

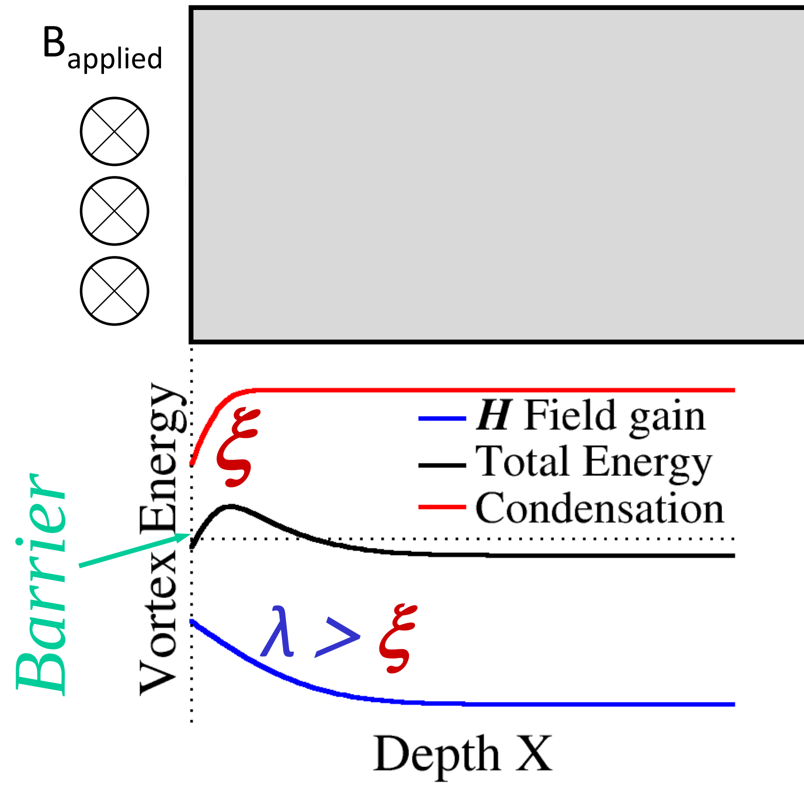
Superheating Field

Why a superheating field?



Energy cost: creation of normal conducting vortex core

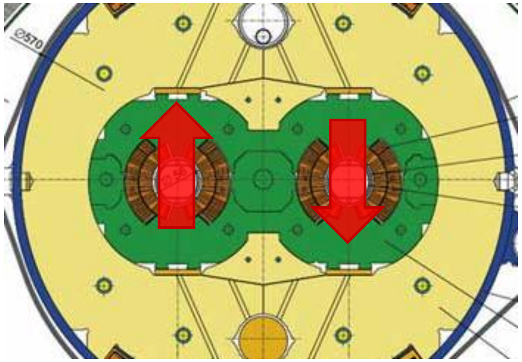
Energy benefit: flux from high magnetic field region into low magnetic field region



Costly core ξ enters first; gain from field λ later

Slide adapted from J. P. Sethna

Selected Superconductors



- NbTi (magnet quality):
  - Lots of pinning centers – H_{c2} ~15 T
  - T_c ~9-10 K, ductile
- Niobium (SRF quality):
  - Robust barrier to magnetic flux – H_{sh} ~0.2 T
  - T_c ~9 K, ductile
- Nb_3Sn (can be either!):
  - Can be made with pinning centers – H_{c2} ~ 30 T
  - Predicted robust barrier to flux – H_{sh} ~0.4 T?
  - T_c ~18 K, brittle

Fabrication of SRF Cavities

- Used in accelerators: Pb and Nb, either bulk or sputtered
- Many film deposition methods researched: ECR, ALD, CVD, HPCVD, MOCVD, HiPIMS, e-beam, thermal vapor diffusion, liquid diffusion, co-sputtering+annealing, cathodic arc deposition
- Many alternative superconductors considered

Experimental Properties of Promising Materials

Material	λ(0) [nm]	ξ(0) [nm]	B_{sh} [mT]	T_c [K]	$\rho_n(0)$ [μΩcm]
Nb	50	22	210	9.2	2
Nb_3Sn	111	4.2	$\boxed{410}$	18	8
MgB_2	185	4.9	210	$\boxed{40}$	0.1
NbN	375	2.9	160	16	144

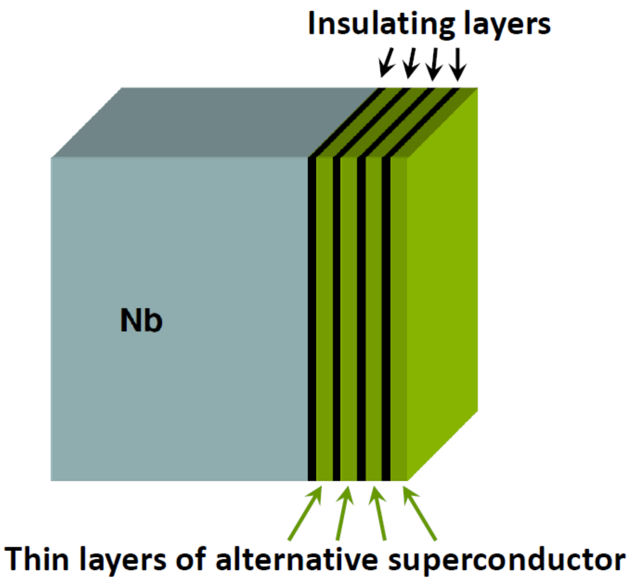
Parameters for: Nb from [1] assuming RRR = 10; Nb_3Sn from [2]; NbN from [3]; MgB_2 from [4] and [5]. B_{sh} for Nb found from equation in [6] and for others calculated from [7]. B_c used to calculated B_{sh} found from [8] eq. 4.20.

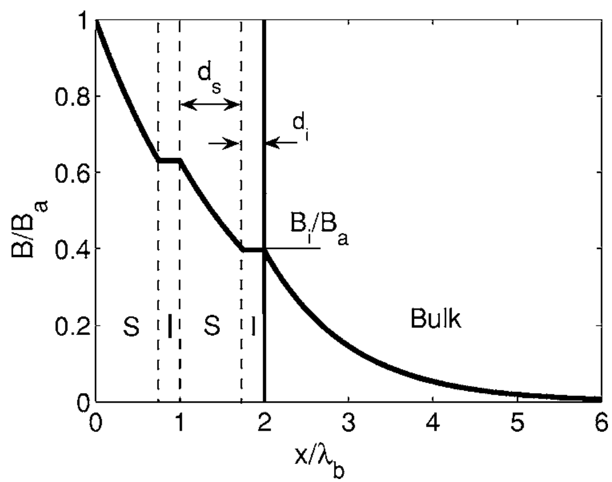
[1] B. Maxfield andW. McLean, Phys. Rev. 139, A1515 (1965).
[2] M. Hein, *High-Temperature Superconductor Thin Films at Microwave Frequencies* (Berlin: Springer, 1999).
[3] D. Oates, et al., Phys. Rev. B 43, 7655 (1991).
[4] Y. Wang, T. Plackowski, and A. Junod, Physica C 355, 179 (2001).
[5] X.X. Xi et al., Physica C, 456, 22-37 (2007).
[6] A. Dolgert, S. Bartolo, and A. Dorsey, Erratum [Phys. Rev. B 53, 5650 (1996)], Phys. Rev. B 56, 2883 (1997).
[7] M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).
[8] M. Tinkham, Introduction to Superconductivity (New York: Dover, 1996).

Material parameters vary with fabrication. References were chosen to try to display realistic properties for polycrystalline films.

Multilayer Films

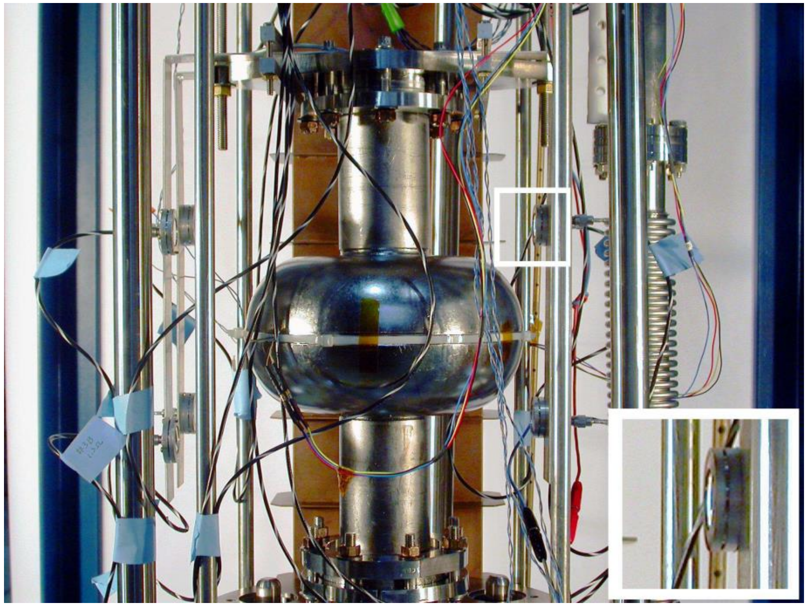
- Alternative geometries considered, including multilayer SIS' films studied in depth
- No significant increase predicted for maximum flux-free field [Posen et al. 2013, Kubo et al. 2013, Gurevich 2015]

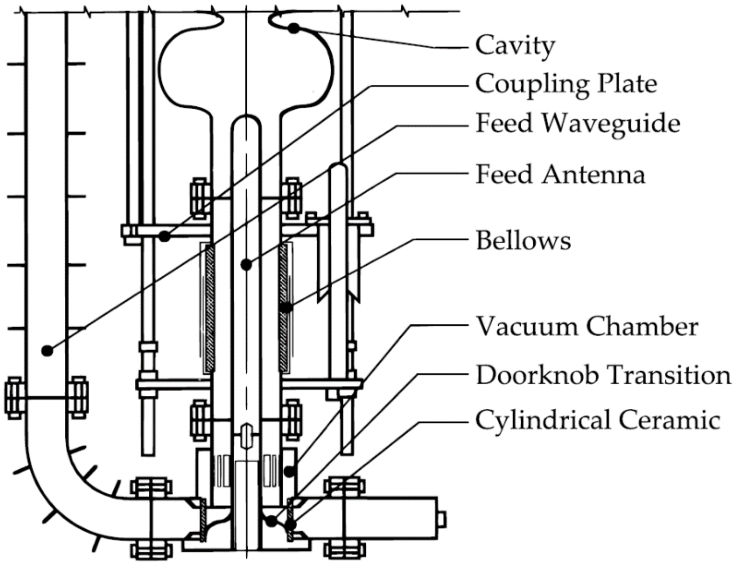


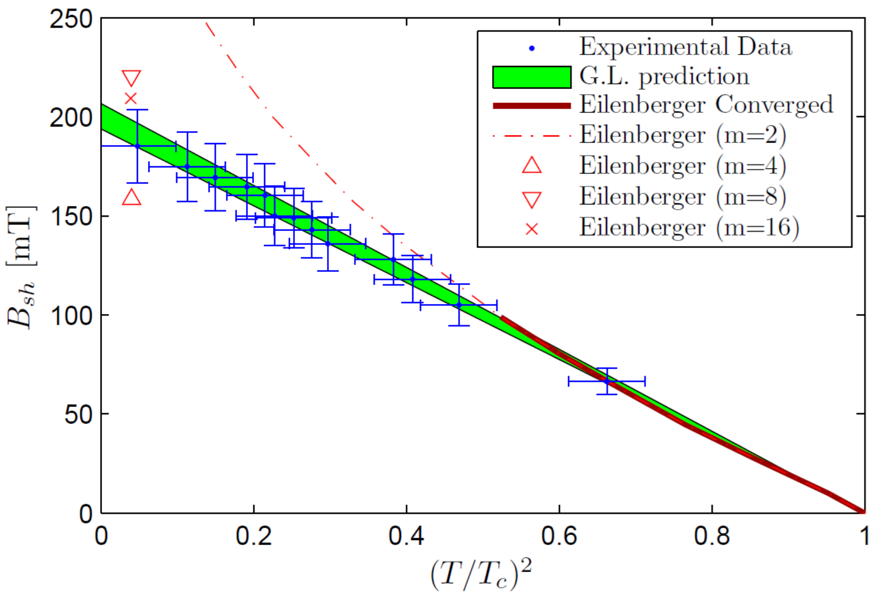


Images adapted from A. Gurevich, APL 012511 (2006)

Pulsed Quench Field



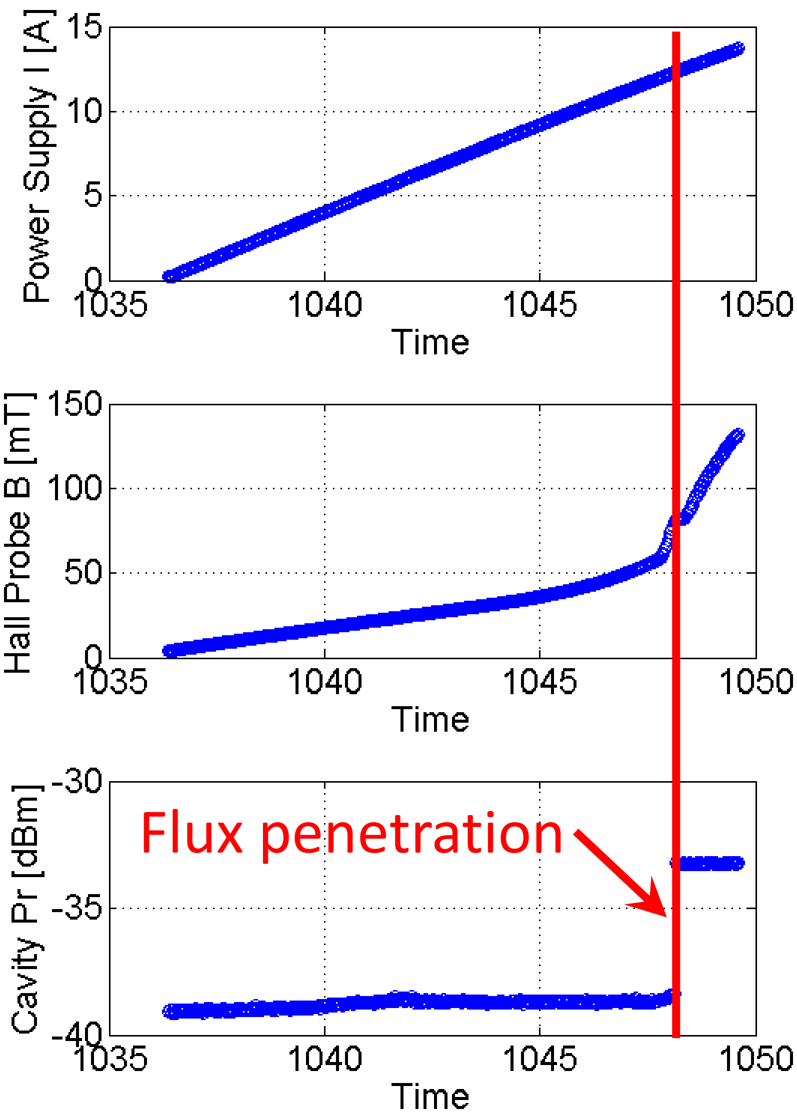


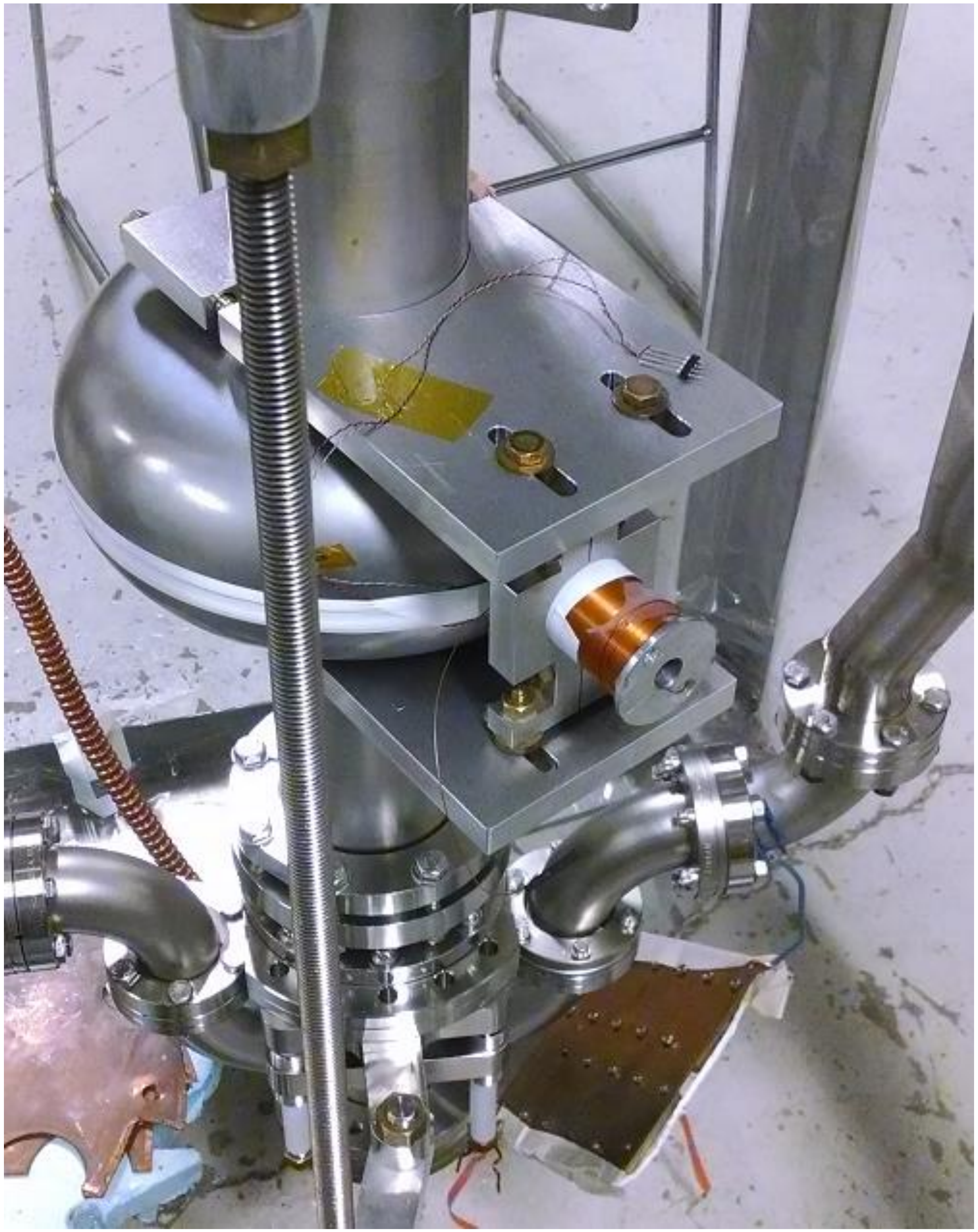


[Radio Frequency Magnetic Field Limits of Nb and Nb_3Sn](#)

S. Posen, N. Valles, and M. Liepe, *PRL* 115, 047001 (2015).

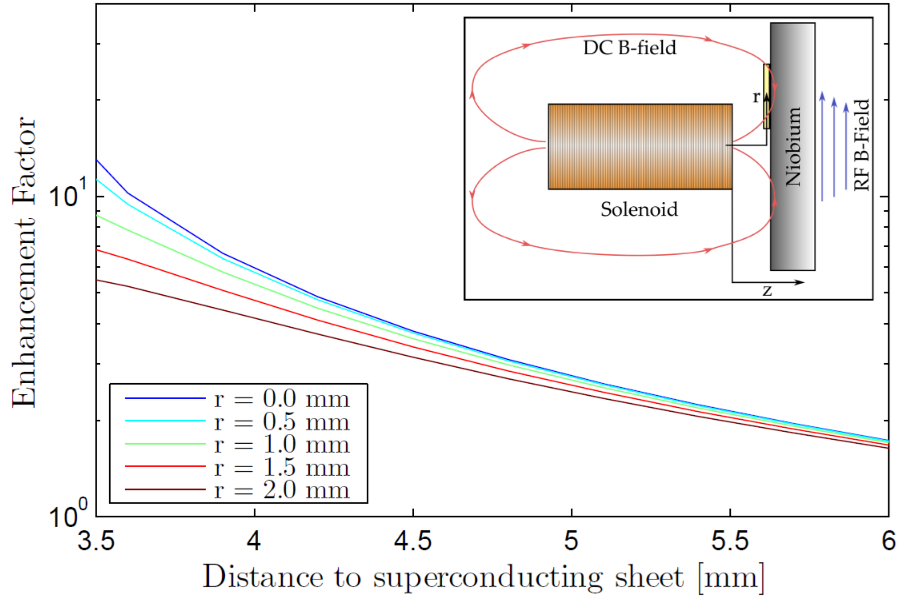
DC Flux Penetration

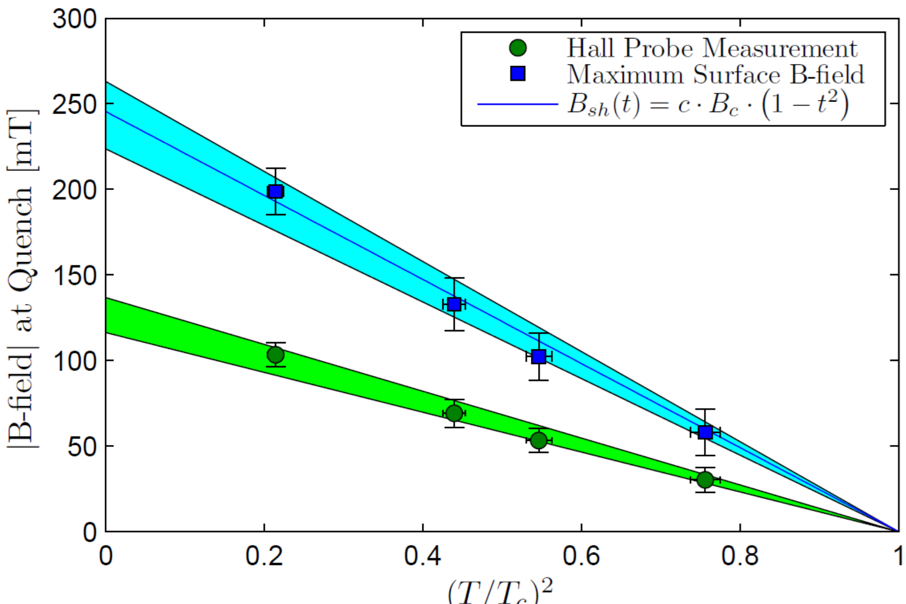


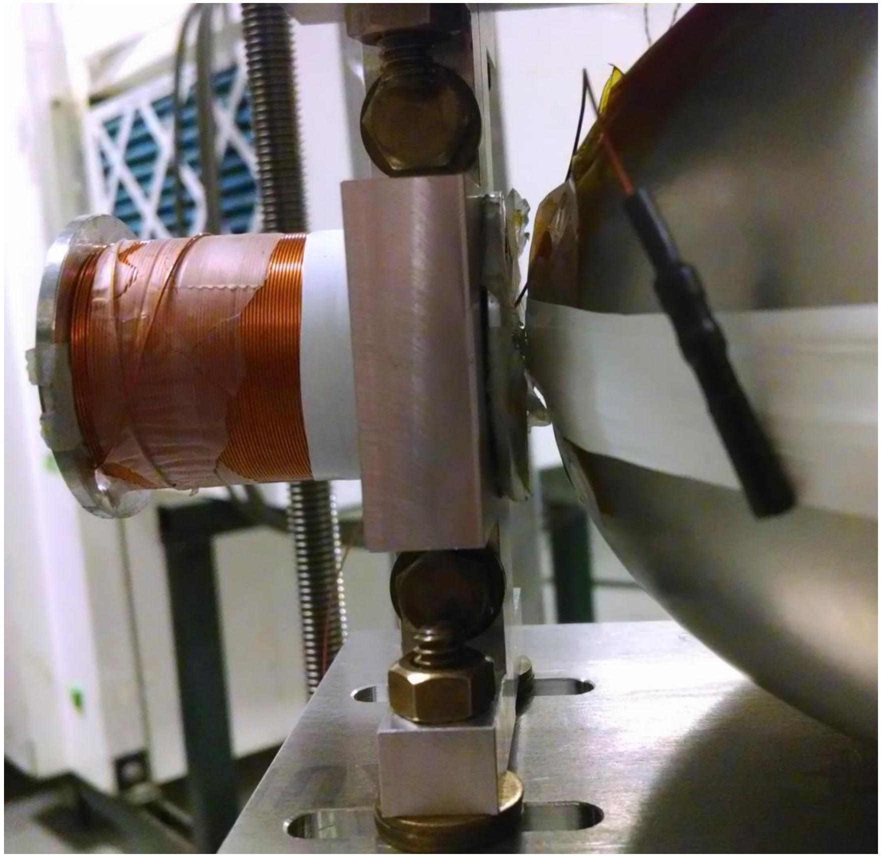


See Nick Valles's thesis, Cornell University, 2014

DC Flux Penetration







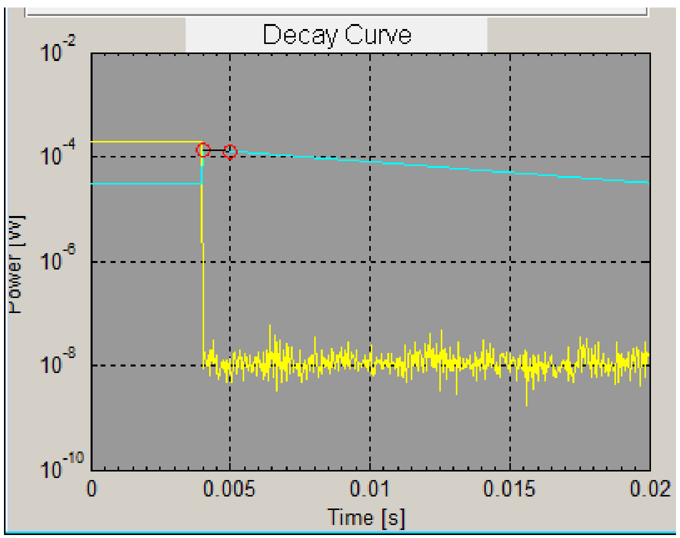
[See Nick Valles's thesis, Cornell University, 2014]

Fermilab Q_0-drop from DC Magnetic Field

$B_{DC} = 0$ T

Measurement Results

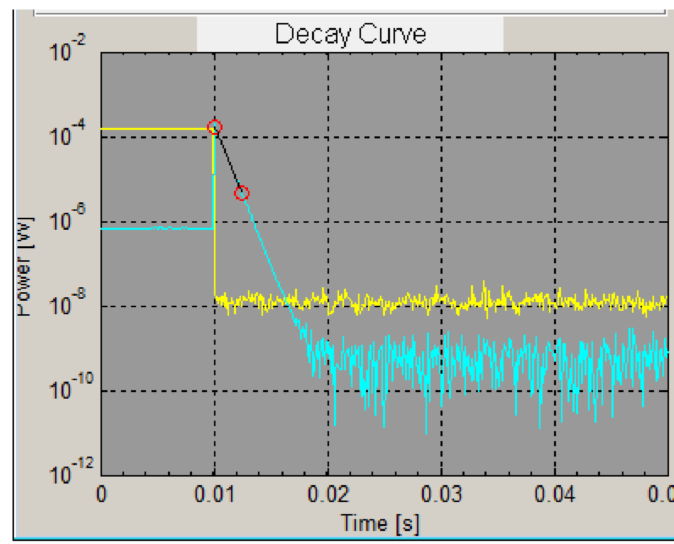
Quantity	Value
Quality Factor	1.351e+008
Eacc [MV/m]	4.23
Beta_R	0.514
Beta_E	0.525



After $B_{DC} = 0.3$ T

Measurement Results

Quantity	Value
Quality Factor	9.908e+006
Eacc [MV/m]	1.07
Beta_R	0.899
Beta_E	0.743



Raw data measured by Nick Valles, Cornell University, 2013

Takeaway

- Realistic expectation: B_{max} ~ 0.2 T at walls of superconducting cavity to maintain high Q_0
- Alternative materials may increase limit up to 0.5 T with a few years of development

Possible Workaround

- Poloidal field coils
- Large field in cavity interior
- Smaller field at walls